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# Mechanical and Thermal Properties of Ultra-High Carbon Steel Containing Aluminum

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**Abstract.** The properties of ultrahigh carbon steels (UHCS) are strongly influenced by aluminum additions. Hardness studies of quenched UHCS-Al alloys reveal that the temperature for the start of transformation increases with increases in aluminum content. It is shown that this change is a function of the atomic percent of solute and of the valence state when comparisons are made with UHCSs containing silicon and tin as solutes. The thermal expansion of UHCSs with dilute aluminum additions shows no discontinuity in the vicinity of the ferrite-austenite transformation temperature. This is the result of a three phase region of ferrite, carbides and austenite. The slope of the expansion curve is higher in the austenite range than in the ferrite range as a result of the dissolution of carbon in austenite with temperature. Processing to achieve a fine grain size in UHCS-Al alloys was principally by hot and warm working (HWW) followed by isothermal warm working (IWW). The high temperature mechanical properties of a UHCS-10Al-1.5C material show nearly Newtonian-viscous behavior at 900 to 1000°C. Tensile elongations of 1200% without failure were achieved in the 1.5%C material. The high oxidation corrosion resistance of the UHCS-10Al materials is described.

## Introduction

Research on ultrahigh carbon steels (UHCSs) have been investigated at Stanford University and at Lawrence Livermore National Laboratory over a number of years that began in the 1970s [1]. Initial studies were to develop new thermal-mechanical processes for creating ultra-fine ferrite grain sizes. The end-purpose was to develop superplastic materials and to understand better the mechanisms of superplastic flow. Subsequent studies were centered on the mechanical behavior of the ultra-fine grained materials at ambient temperature. These studies have been described in several articles [2-4]. In 1989, a commercialization project was funded at the Lawrence Livermore National Laboratory by the U.S. Department of Energy in their newly created Steel Initiative Program. This program, in collaboration with industrial partners, and Stanford University, was centered on developing UHCSs that could exhibit high strain rate superplasticity and, more importantly, at low flow stresses. The program continued until 1994 and demonstrated the commercial feasibility of UHCS for industrial application. Much of the work was centered on UHCS containing aluminum. The aluminum was added because it is a ferrite stabilizer. This is an important quality because it increases the temperature range for the transformation to austenite. Hence, the fine-grained ferrite material can be taken to higher temperature where the increased diffusivity of ferrite iron will enhance superplastic flow. The UHCS containing aluminum, ranging from 0.5 to 10 wt % aluminum were investigated with carbon contents ranging from 0.7 to 1.8 weight percent. On one end of the aluminum range, the mechanical properties were studied for their superplastic behavior [5, 6] and for their low temperature mechanical properties [7]. A similar

study was made on the other end of the aluminum range. Specifically, a UHCS-10Al-1.25 C material was evaluated for its superplastic behavior [8]. A study of the same material but with different amounts of carbon, 0.7 and 1.5%, was evaluated for its mechanical properties [9]. These results are described in the present investigation together with a summary of unpublished data on the thermal properties of a number of UHCSs.

## Materials, Processing and Experimental Procedures

Two UHCSs are reported here. The compositions of the UHCSs, in weight percent, are UHCS-10Al-1.5Cr-0.5Mn-0.1Mo-1.5C and UHCS-10Al-1.5Cr-0.5Mn-0.7C. These vacuum cast ingots were forged at 1100°C into 50mm cross-section bars. Cubes taken from the bars were thermo-mechanically processed into sheet by a rolling process in two stages. Hot-and-warm working (HWW) continuously from 1230°C to 800°C yielded 12 mm plates. After HWW processing, the plates were isothermally warm worked (IWW) at about 815°C to 3 mm plates. The grain size of the as processed material was 3  $\mu\text{m}$  for the 1.5C material and 35  $\mu\text{m}$  for the 0.7C material. The grain size in the coarse grained UHCS was reduced to 7  $\mu\text{m}$  by a subsequent cold rolling and recrystallization process. High temperature tensile tests of the 3mm plates were done in air in an Instron machine conducted at various crosshead speeds. Change in strain-rate-tests was performed over small strain increments to study the creep behavior of the fine grained material. Tensile ductility was determined by elongation-to-failure tests at constant cross-head speed.

## Results and Discussion

The results and discussion are described for five properties related to ultrahigh carbon steels containing aluminum. These are: (A) the influence of quenching temperature on the hardness of the UHCS-10Al-1.5C material, (B) the influence of aluminum content (including other ferrite stabilizer elements) on the temperature at which transformation to austenite begins to be observed, (C) the influence of carbon content on the thermal expansion coefficient of UHCS-Al alloys, (D) the high temperature superplastic properties of UHCS-10Al-1.5C material and (E) the influence of carbon on the tensile properties of UHCS-10Al. at low temperature.

**Hardness.** The hardness versus quenching temperature of the UHCS-10Al-1.5C material is shown in Fig. 1. The starting material was the thermo-mechanically processed material that had a ferrite grain size of 3  $\mu\text{m}$  containing 0.1  $\mu\text{m}$  carbide particles. The hardness of the quenched sample is seen to decrease slightly from 700 to 900°C in the two phase region, ferrite ( $\alpha$ ) plus carbides ( $\kappa$  as  $\text{Fe}_3\text{AlC}$ ). Above 900°C, transformation to austenite ( $\gamma$ ) begins. Three phases co-exist between 900 and 1100°C, namely  $\alpha + \gamma + \kappa$ . Above 1100°C, only one phase exists, austenite, a solid solution of aluminum and carbon in face-centered-cubic iron. Fig. 2 illustrates microstructures of the quenched material in the three-phase region. Figs. 2a and 2b show the structure at 950 and 1000°C. The austenite phase consists of bulbous shaped grains, and the carbides are in

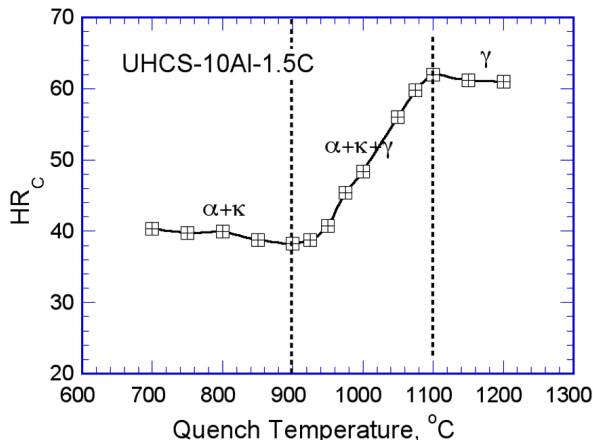


Fig.1. Hardness vs. quench temperature for UHCS-10Al-1.5C steel.

the form of particles about 1 to 2  $\mu\text{m}$  in size with many straight sides. The remaining phase is ferrite grains, about 50% by volume at 950 $^{\circ}\text{C}$  and 30% at 1000 $^{\circ}\text{C}$ . The average linear grain size is less than 5  $\mu\text{m}$ . Figure 2c shows the microstructure at 1075 $^{\circ}\text{C}$  where the carbides are mostly dissolved with the grain size equal to about 12  $\mu\text{m}$ .

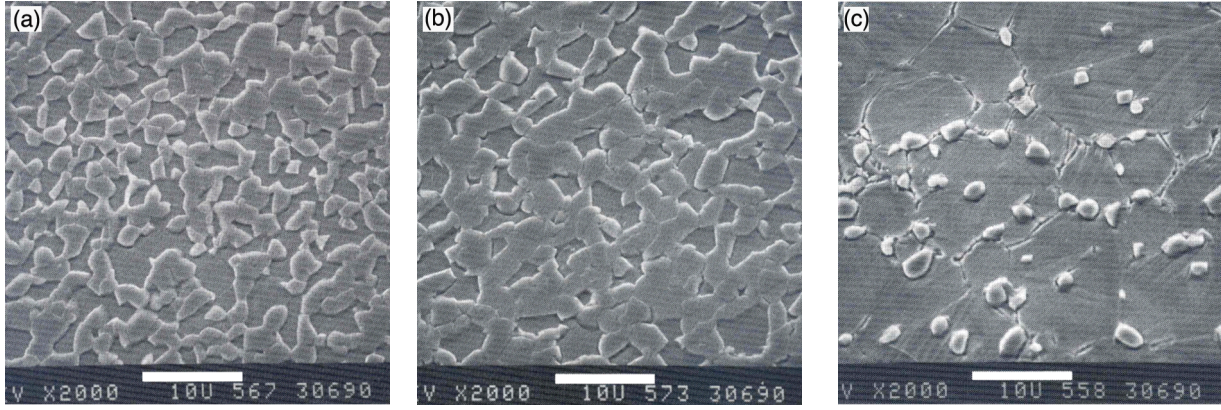


Fig. 2. Microstructure of UHCS-10Al-1.5C steel. (a), (b) and (c) represent the microstructure of the steel at 950, 1000 and 1075 $^{\circ}\text{C}$  as observed after quench to room temperature.

**Transformation Temperature.** The hardness-quench method, Fig. 1, was used to establish the austenite start temperature for the other UHCS-Al materials. Differential thermal analysis was also used to confirm the transformation temperatures. A similar approach was used to study the influence of ferrite stabilizers, namely Cr, Si and Sn on the austenite start temperature for UHCS containing 1.25 wt % of carbon. Fig. 3 summarizes the results of this work [10]. The austenite start temperature is shown to be a linear function of atomic percent of the ferrite stabilizer element times the valence of the element. This correlation shows that the increase in the austenite start temperature is not only related to the increase in atomic concentration of solute atoms but also to the increase in the density of their valence electrons.

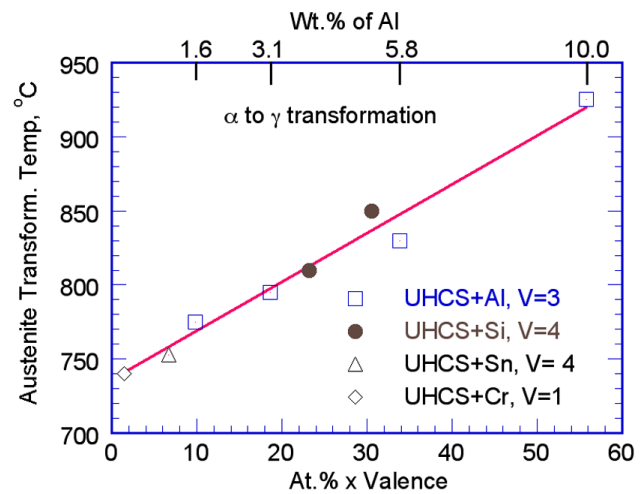


Fig. 3 Austenite transformation temperature as influenced by at% and valence of alloying elements in UHCS-1.25 wt%.

**Thermal Expansion.** Thermal expansion tests were pursued at the Lawrence Livermore National Laboratory on a number of UHCS-1.6Al materials containing different amounts of carbon. Fig. 4 illustrates the volume expansion, in percent, as a function of temperature. Included in the graph are data for four commercial grade Fe-C steels, 1010, 1018, 1045 and 1090. These steels show the decrease in volume at the  $A_1$  transformation temperature reflecting the formation of the dense gamma austenite phase. On the other hand, the UHCS-Al alloys do not show a decrease in the volume during heating. In the case of the UHCS-1.25C, the UHCS-1.6Al-1.25C and the UHCS-1.6Al-1.6Cr-1.5C materials, a slightly lower slope is noted around the start of transformation. This is a reflection of

the gradual increase in austenite as it enters the three phase region. Further heating reveals a steep rise in the expansion coefficient in the temperature range from 800 to 1000°C that represents the gradual dissolution of the carbides into the gamma lattice. Thus, the calculated expansion coefficient is not a fundamental value related to the lattice constant of fcc iron. It represents the ever-changing structure of iron with increase in temperature with more carbon incorporated into the fcc lattice. The expansion coefficient above 1100°C becomes a constant and is the same for all UHCSs as well as the commercial Fe-C steels. It describes the expansion of the face-centered cubic iron lattice. The difference in the amount of volume change with carbon content, at a given temperature, reflects the increasing contribution of all dissolved carbon in the gamma iron lattice.

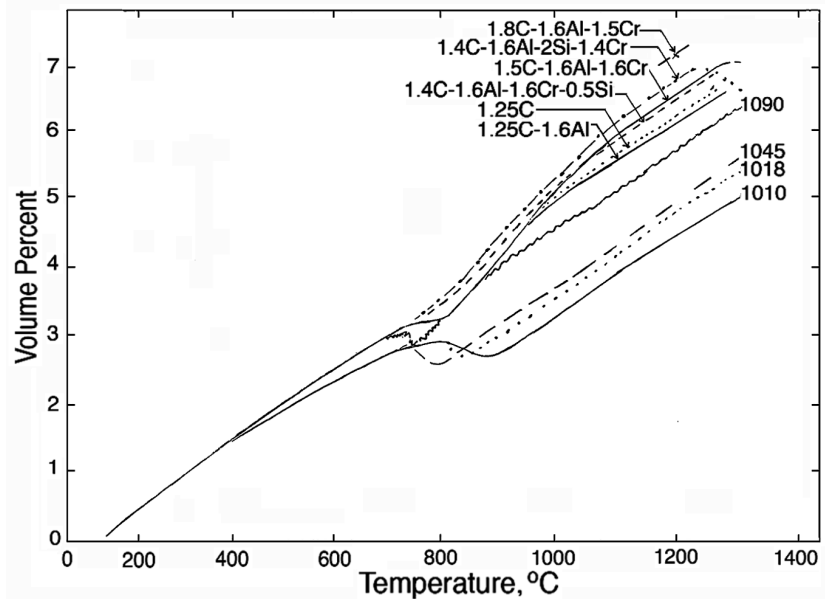


Fig. 4. Dilatometry results of various UHCS materials and four carbon steels 1090, 1045, 1018 and 1010.

**Superplasticity.** The superplastic behavior of the UHCS-10Al-1.5C material was evaluated by tensile tests over the temperature range from 750 to 1000°C. Reference to Fig. 1 shows that the tests done from 750 to 900°C were in the two phase region,  $\alpha + \kappa$ , and tests done above 900°C were in the three phase region,  $\alpha + \kappa + \gamma$ . This distinction is important, because the tests done below 900°C represent constant structure conditions whereas those above 900°C represent continuous changes in structure with the amount of the  $\alpha$  and  $\kappa$  phases dissolving and the amount of  $\gamma$  increasing with increase in temperature. Fig. 5 shows how the flow stress of the UHCS-Al material changes with temperature at two different strain rates,  $10^{-2}$  and  $10^{-4} \text{ s}^{-1}$ , covering the whole temperature range studied. The data reveal the expected decrease of the flow stress with an increase in temperature in the two-phase region. A sudden change occurs in the three phase region where the flow stress remains unchanged with increase in temperature. This is because,

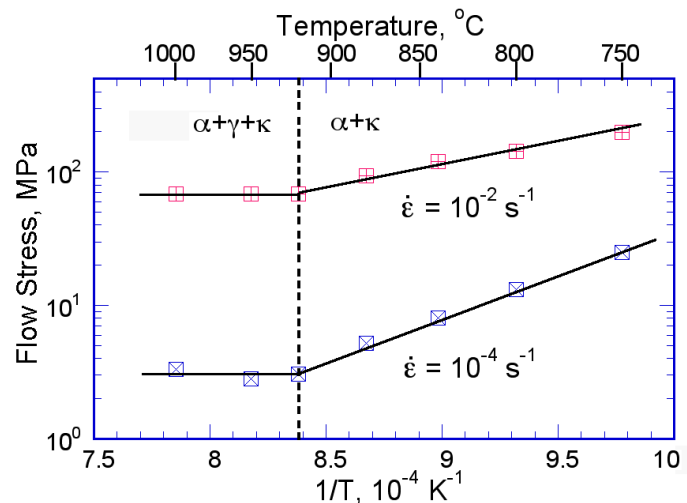


Fig. 5. Flow stress at elevated temperatures in UHCS-10Al-1.5C material.



at increasing temperature, there is a compensating balance between the decrease in strength from the  $\alpha$  phase and the increase in strength from the stronger  $\gamma$  phase. The stress exponent,  $n$ , is readily calculated in the three-phase region from the data in Fig. 5. The value is the logarithmic ratio of the change in strain rate to the logarithmic ratio of change in flow stress, yielding  $n = 1.5$ . This small value of  $n$ , approaching Newtonian viscous behavior ( $n = 1$ ) indicates superplastic flow behavior is expected. The insensitivity of the flow stress with temperature is a very positive property in superplastic forming of sheet products by gas pressure forming. This is because the control of temperature may not require careful monitoring. The same observation is described by Ruano et al [11] for a fine-grained UHCS-3Si-1.25C alloy when tested in a lower temperature region than observed here. Fig. 6 shows the very high elongation obtained in the UHCS-10Al-1.5C when tested in air at  $1000^{\circ}\text{C}$  at a high initial strain rate of  $3.3 \times 10^{-2} \text{ s}^{-1}$  (200 % per minute). The sample was deformed by over 1200% with no signs of necking. The test was stopped because of the limiting size of furnace used. The large amount of aluminum prevents oxidation. This means that superplastic forming of components can be made without a protective environment. Sulzer Brothers of Winterthur, Switzerland successfully formed a complex ring component with UHCS containing 9.3%Al and 1.23%C in a five-minute forming operation [12, 13].

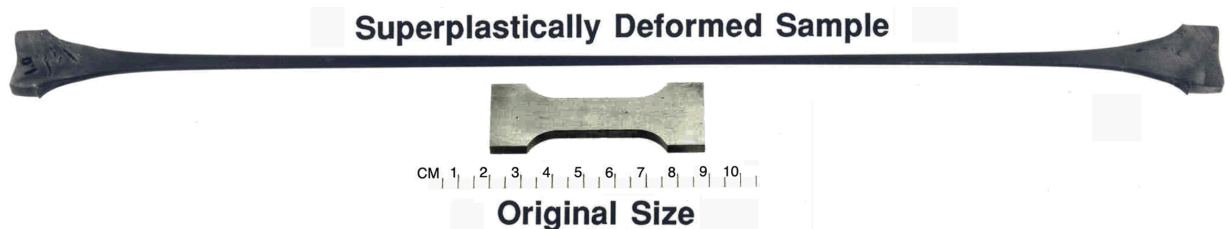


Fig.6. Tensile superplasticity demonstrated in UHCS-10Al-15C at  $950^{\circ}\text{C}$  at a strain rate of 200% per minute to  $>1200\%$  strain without failure.

**Tensile Properties.** A limited number of tests were done on the mechanical properties of UHCS-10Al materials at room temperature. Fig. 7 shows engineering stress-engineering strain curves for two carbon contents. The UHCS-10Al-1.5C material showed a tensile strength of 1100 MPa with 5% elongation. It was this low tensile ductility that led to a study of the similar composition material but with a lower carbon content of 0.7C. The ductility was significantly enhanced as shown in Fig. 7. A decrease in the carbon content showed a tensile strength of 850 MPa with 22% elongation. The high aluminum UHCS-0.7C material, with its high ductility at room temperature and superplastic behavior at high temperature, were considered for possible application as automobile exhaust pipes.

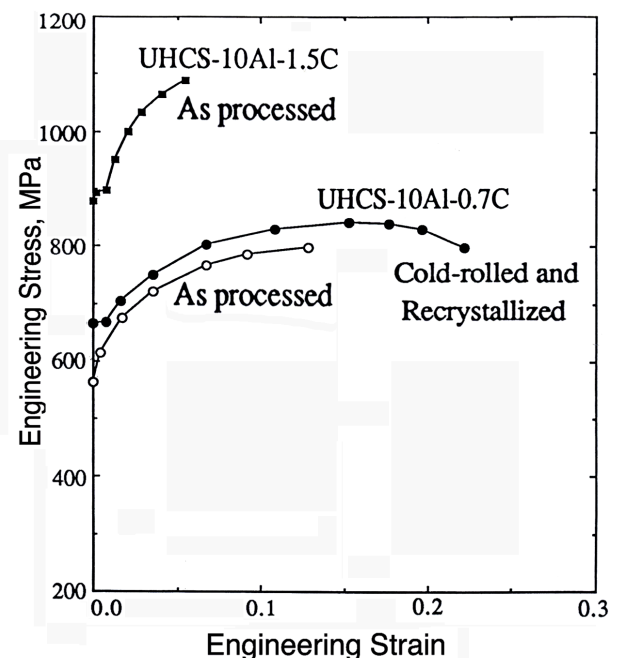


Fig. 7. Mechanical properties of UHCS-10Al materials at room temperature.

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